ON-SITE EFFICIENCY EVALUATION FOR IN-SERVICE INDUCTION MOTORS

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Key words: Analytical method, Induction motors, Operating efficiency, On-site evaluation.

An analytical method for energy efficiency estimation in the case of large in-service low voltage three phase asynchronous motors is proposed, tested and discussed. Starting from the steady-state operating motor equations of the modified per phase equivalent circuit model of the machine, a robust symbolic software package was generated. The developed algorithm only requires the basic power quality parameters as measured at the induction motor input and its nameplate data. Thus, a rather accurate and less intrusive method for field efficiency evaluation of in-service motors is described. In order to validate the results, five induction motors were tested. The obtained values for both operating power factor and efficiency are compared with those reported by the manufacturer specifications.

1. INTRODUCTION

In most of the industrial units, the motor-driven systems use more than two-thirds of the total electric energy absorbed [1]. Consequently, these motorized systems and especially those driven by large or critically important motors are subject of numerous energy evaluation or audit studies [2]. These investigations mainly focus on a better estimation of the in-service motor operating efficiency and power factor. Accurate values of these two energy parameters could lead to the identification of any potential energy efficiency gains and reliability enhancements. Thereby, passive (low consumption devices, power factor correction systems, thermal isolation etc.) or active (variable speed drivers, monitoring devices, energy saving analysis software etc.) energy efficiency measurement [3, 4] could be later accordingly selected. International standards for induction machine losses and efficiency determinations require both no-load and blocked rotor measurements [5]. The latter are impossible to be carried out in the case of an on-site determination, when the motor cannot be separated from its driven load. Thus, various in-service efficiency evaluation methods have been developed [6, 7].

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Valuable comparative review studies of these main procedures in terms of their physical principle, accuracy and intrusiveness are detailed in [8, 3].

This paper presents a novel minimally invasive method for large (with rated power around 100 kW) in-service S1 (duty cycles) low-voltage induction motors operating efficiency determination. Relying on the symbolic analysis of the slightly modified per phase equivalent circuit model of the induction motor, and requiring only the basic input power quality parameters along with the machine nameplate data, this method could represent a reliable alternative for motor field testing efficiency. Additionally, the developed algorithm also analyzes the opportunity of replacing the tested in service-motor with a properly sized model that additionally addresses some other technical demands.

2. IN SERVICE EVALUATION OF THE INDUCTION MOTOR OPERATING EFFICIENCY

The implementation of proposed method, as Fig. 1 shows, only ask for a three phase PMD (Performance Measuring and Monitoring Device) such a portable power quality analyzer connected both to the current and voltage sensors and a general computing environment where a special design software package is installed. The relevant electric data collected from the electric system drive via current and voltage clamps and motor nameplate reading, are transferred by the PMD to the computational system which generates a real-time operating energy efficiency report. Supplementarily, the developed algorithm also uses a large periodically updated database, where all the electric motor parameters supplied by the major manufacturers are stored.

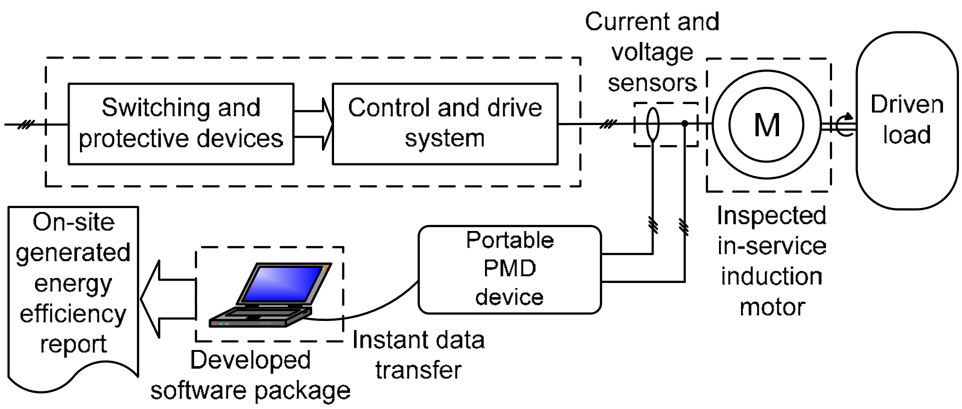

Fig. 1 – Architecture of the in-service evaluation method of the induction motor operating efficiency.

2.1. MATHEMATICAL MODEL OF THE EFFICIENCY PARAMETER DETERMINATION

In order to quantitatively express the motor operating efficiency and power factor in terms of machine parameters and its load factor, a particular per phase equivalent circuit model, specific to the large power class motors [9, 10] was used, as depicted in Fig. 2.

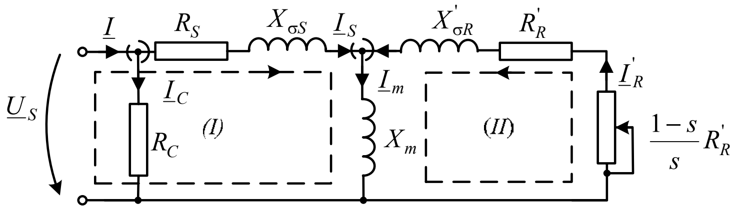

Fig. 2 – Per-phase electric circuit model of the large power induction motor.

The entire motor steady-state operating point can be mathematically predicted by applying nodes and loops equations for the above circuit model. That leads to the following system of equations:

$$\begin{aligned} &\underline{U}_S = [R_S + \mathrm{j}(X_{\sigma S} + X_m)]\underline{I}_S + \mathrm{j}X_m\underline{I}'_R, \\ &\mathrm{j}X_m\underline{I}_S + \left[\frac{R'_R}{s} + \mathrm{j}\left(X'_{\sigma R} + X_m\right)\right]\underline{I}'_R = 0, \quad s = \frac{n_S - n}{n_S}, \\ &\underline{U}_S = \underline{I}_C R_C,\ \underline{I}_m = \underline{I}_S + \underline{I}'_R,\ \underline{I} = \underline{I}_S + \underline{I}_C, \end{aligned} \tag{1}$$

where the following notations were used: $\underline{U}_S$ phase voltage, $\underline{I}_S$ stator phase current, R_S stator winding resistance, $X_{\sigma S}$ stator winding leakage reactance, X_m magnetizing reactance, R_C core loss resistance, $\underline{I}_C$ current core, R'_R rotor resistance referred to the stator, $X'_{\sigma R}$ rotor winding leakage reactance referred to the stator, $\underline{I}'_R$ rotor current referred to the stator and s is motor slip defined as the percent relative difference between the synchronous speed of magnetic field n_S and the shaft rotating speed n.

One can notice from the above equations that for a certain stationary operation point (with specific values of the supply voltage and frequency) of the drive system, all its electric characteristics are mainly determined by induction motor parameters and slip value. The last quantity depends on the load factor, usually defined as the mechanical output power shaft P with respect to the rated value P_n. Since experimental determination of the motor power shaft often raises difficulties, the here adopted motor load factor, further denoted by β, was defined as the measured active power P_A with respect to the rated active power P_{An}. By a simple nameplate reading, the absorbed rated active power is the ratio of the rated motor power P_n relative to the rated efficiency η_n. Thus, the whole efficiency investigation of the in-service induction motor is performed by using mainly on-site measured electric parameters.

The main condition for further computation of any steady-state regime of the machine is an accurate determination of the slip. That could be achieved by using the per- phase motor circuit model and the absorbed measured active power:

$$P_A = P_S + P_C + P_R + P_{Conv} = 3\left(R_S I_S^2 + R_C I_C^2 + R_R^{'} I_R^{'2} + R_R^{'} I_R^{'2} \frac{1-s}{s} \right), \qquad (2)$$

where $P_S = 3R_S I_S^2$ and $P_R = 3R_R^{'} I_R^{'2}$ are stator and rotor Joule losses, respectively, $P_C = 3R_C I_C^2$ are core losses and $P_{Conv} = 3R_R^{'} I_R^{'2}(1-s)/s$ is the converted electrical to mechanical power, which covers the output shaft power P and rotational losses: (friction and windage losses P_{fw} and stray losses P_{stray}).

Using a computation algorithm, the relation of slip s in terms of motor per phase equivalent circuit parameters and load factor β, can be extracted as:

$$s = 0.5 R_R^{'} (-a \pm \sqrt{a^2 - 4b}),$$

where

$$a = \frac{X_m^2 (c - 2R_S)}{R_S X_R^{'2} (c - R_S) - (X_S X_R^{'} - X_m^2)^2} \quad b = \frac{R_S (c - R_S) - X_S^2}{R_S X_R^{'2} (c - R_S) - (X_S X_R^{'} - X_m^2)^2}, \qquad (3)$$

$$\text{with } c = \frac{3U_S^2}{\beta P_{An} - 3\left(U_S^2 / R_C\right)},$$

$$\text{and } X_S = X_{\sigma S} + X_m, \; X_R^{'} = X_{\sigma R}^{'} + X_m, \; \beta = \frac{P_A}{P_{An}}.$$

2.2. OPERATING EFFICIENCY AND POWER FACTOR

In order to express the operating efficiency η of the induction motor, along with the absorbed active power P_A, the shaft power P is required. This last quantity can be evaluated in terms of converted electrical to mechanical power P_{Conv} and rotational losses P_{rot} :

$$P = P_{Conv} - P_{rot} = P_R \frac{1-s}{s} - P_{rot} = 3R_R^{'} I_R^{'2} \frac{1-s}{s} - P_{rot} \text{ and } \eta = \frac{P}{P_A}. \qquad (4)$$

One way to estimate the rotational losses, assumed invariable with the motor speed, is to use the rated slip s_n and rated output power P_n of the inspected induction motor:

$$P_{rot} = P_{Rn} \frac{1 - s_n}{s_n} - P_n ,$$

$$\text{with } P_{Rn} = \frac{R_R^{'}}{R_S} \frac{s_n^2 X_m^2}{R_R^{'2} + s_n^2 X_R^{'2}} P_{Sn} , \tag{5}$$

$$P_{Sn} = 3R_S \frac{U_S^2 (R_R^{'2} + s_n X_R^{'2})}{s^2 [R_S^2 X_R^{'2} + X_S (X_R^{'} - X_m^2)^2] + 2 s_n^2 R_S R_R^{'} X_m^2 + (R_S^2 + X_S^2) R_R^{'2}} .$$

Similarly, for the power factor *PF* evaluation, along the active power expression, the absorbed reactive power Q_A formula is also required. The latter will be also obtained using the machine circuit model:

$$Q_A = 3X_{\sigma S} I_S^2 + 3X_{\sigma R}^{'} I_R^{'2} + 3X_m I_m^2 = Q_{\sigma S} + Q_{\sigma R} + Q_m ,$$

with

$$Q_{\sigma S} = 3 \frac{U_S^2 (X_S - X_m)(R_R^{'2} + s^2 X_R^{'2})}{s^2 [R_S^2 X_R^{'2} + (X_S X_R^{'} - X_m^2)^2] + 2s R_S R_R^{'} X_m^2 + (R_S^2 + X_S^2) R_R^{'2}} ,$$

$$Q_{\sigma R} = \frac{X_R^{'} - X_m}{X_S - X_m} \frac{s^2 X_R^{'}}{R_R^{'2} + s^2 X_R^{'2}} Q_{\sigma S}, \quad Q_m = \frac{X_m [R_R^{'2} + s^2 (X_R^{'} - X_m)^2]}{(X_S - X_m)(R_R^{'2} + s^2 X_R^{'2})} Q_{\sigma S} , \tag{6}$$

$$PF = \frac{P_A}{\sqrt{P_A^2 + Q_A^2}} .$$

It is important to mention that the above equations are valid as long as the basic power quality parameters (voltage and current level of unbalance and harmonics pollution) monitored by the PMD device are maintained below the international standard prescriptions levels [11]. Our developed software package will issue a warning whenever these above-mentioned values are exceeded. Moreover, it can automatically derates the two computed energetical parameters according to the motor manufacturer specifications.

Additionally, the problem of replacing the actual in-service motor with a properly sized one is also analyzed. This discussion often arises when the load factor β lies between 50 % and 70 % [2, 9]. The adopted quantitatively study is based on the operating efficiency and power factor estimation of the downsized motor that replaces the actual one. The algebraic differences between the two total power losses difference ΔP expressed in terms of actual operating efficiency η, denoted by ΔP_{η} and the new motor potential operating efficiency η_{new}, denoted by $\Delta P_{\eta_{new}}$ is estimated.

$$\Delta P = \Delta P_{\eta} - \Delta P_{\eta_{new}} = \left(\frac{1}{\eta} - \frac{1}{\eta_{new}} \right) P . \tag{7}$$

As equation (7) reveals, a positive value of ΔP ($\eta_{new} > \eta$) could suggest the benefit of replacing the motor in terms of active power loss diminution. Then the reactive power absorption is also considered, comparing the motor actual reactive power Q_A with the potential reactive power requirement Q_{Anew}, which correspond to a new operating power factor PF_{new}:

$$\Delta Q = Q_A - Q_{Anew} = \left(\frac{1}{\eta} \frac{\sqrt{1 - PF^2}}{PF} - \frac{1}{\eta_{new}} \frac{\sqrt{1 - PF_{new}^2}}{PF_{new}} \right) P . \tag{8}$$

A positive value of the reactive power difference ΔQ will indicate an efficient motor replacement considering the reactive power absorbed of the electric drive system. Relying on the above mentioned restrictions, numerous scenarios are considered by the proposed software. It uses a large, periodically updated available motor database and finally a full report is generated. The chart representation of the motor efficiency analysis and replacement opportunity is presented in Fig. 3, where also the main decisions are displayed.

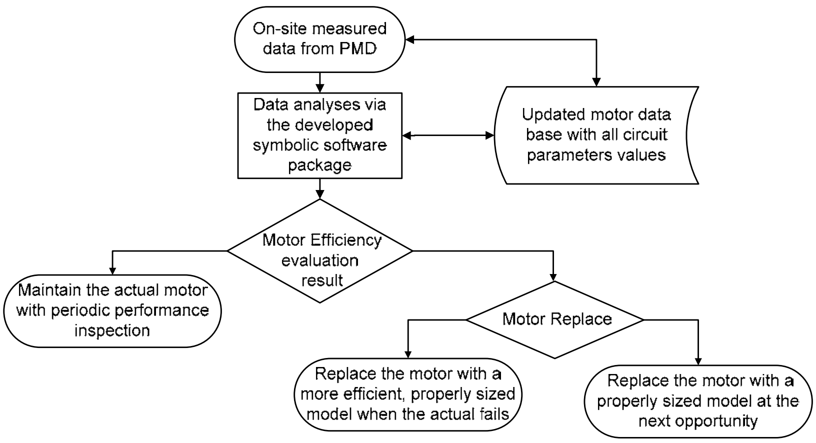

Fig. 3 – Chart representation algorithm of the on-site motor operating efficiency and replacement opportunity analysis.

3. **VALIDATION OF THE EFFICIENCY PARAMETER EVALUATION – CASE STUDIES**

In order to verify the proposed field efficiency evaluation procedure, five motor drive systems that correspond to the method requirements were selected. The rated power of the corresponding low voltage induction motors is comprised between 90 kW and 200 kW. Their driven load being winders or lathes machineries, we can assume a continuous duty cycle. For all the motors, the main nameplate rated parameter values are presented in Appendix 1.

Applying the developed symbolic software to all the tested motors, the operating characteristics for both efficiency (Fig. 4) and power factor (Fig. 5) are obtained.

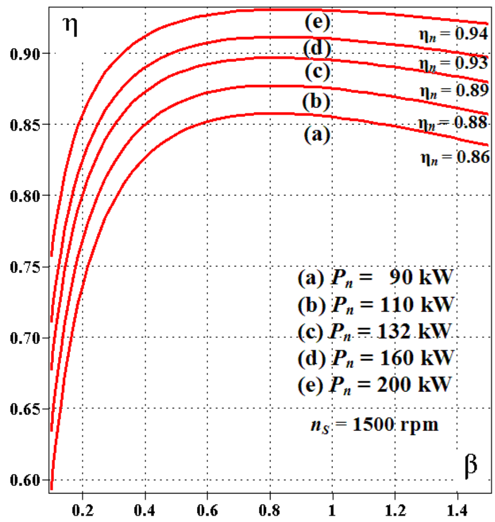

Fig. 4 – Operating motor efficiency characteristics.

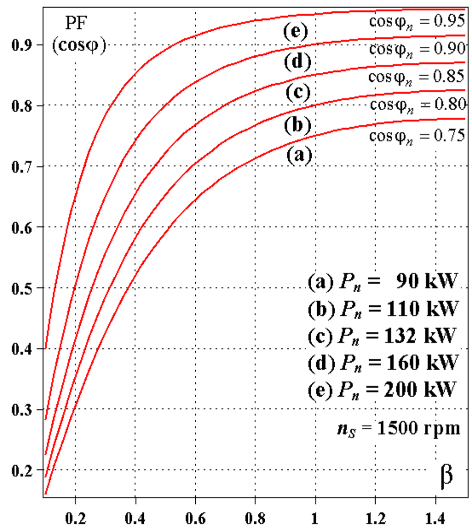

Fig. 5 – Operating motor power factor characteristics.

Taking into account that especially for such large motor units, the majority of manufacturers indicate the operating efficiency and power factors values at specific load factors, a comparative quantitative study was easy to approach. Thus, for these particular load factors, the computed energetical parameters and those taken from motor' documentation fit very well. For instance, Table 1 shows for the 132 kW rated power motor the analytical evaluated operating efficiency and power factor versus the manufacturer indicated values for three different load factors: 0.5, 0.66 and 0.75. One can notice that the difference between the computed and indicated values is insignificant. Additionally, it diminishes with the load factor increase.

Table 1

Comparison between the energetical parameters analytically obtained and those reported by the manufacturer for a 132 kW rated power induction motor at different load factors

Load factor β		1/2	2/3	3/4
Operating Efficiency: η	Manufacturer indicated value	0.796	0.879	0.887
	Proposed method obtained value	0.784	0.878	0.884
Operating power factor: PF	Manufacturer indicated value	0.791	0.833	0.846
	Proposed method obtained value	0.787	0.829	0.842

The software package allows an extended analysis over a large class of motors with the same rated power, but with different values for rated efficiency or power factor. For the above analyzed 132 kW power rated motor, Fig. 6 shows the efficiency variation with respect to the rated efficiency and load factor, while Fig. 7 represents the power factor variation relative to the rated power factor and load factor variation.

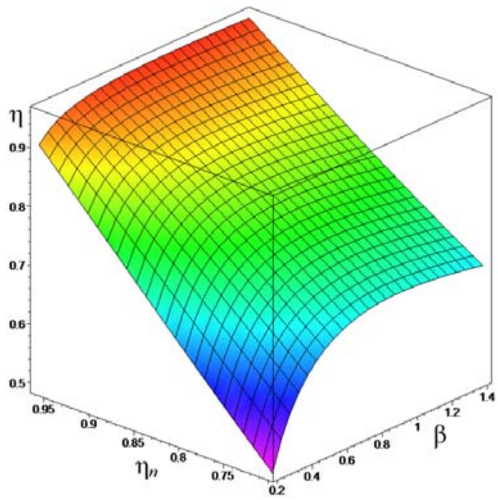

Fig. 6 – Operating motor efficiency variation with respect to rated efficiency and load factor.

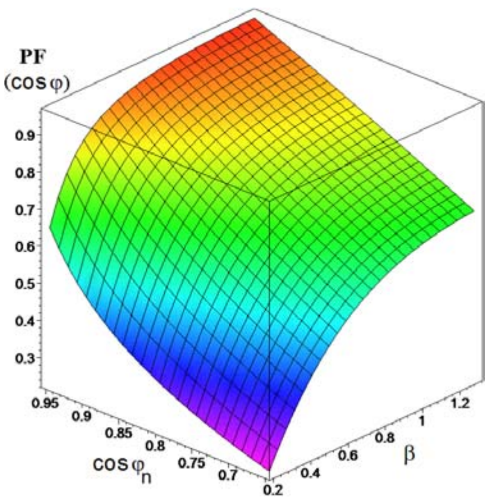

Fig. 7 – Operating motor power factor variation-with respect to rated power factor and load factor.

Aiming to find the most appropriate motor for the electric drive, similar investigations are to be performed for any energy efficiency field motor evaluation.

4. CONCLUSIONS

An analytical method for the main energetical parameters estimation of the in-service induction motors was proposed. The quantitative study is based on the per-phase equivalent circuit model of the machine and requires minimal on-site measured power quality parameters along with nameplate data reading. A software package only using electric parameters as input data (via a fast connection to a PMD) was developed. By accessing a large preloaded motor database (supplied by the major manufacturers), the program accurately returns the operating efficiency and power factor for the inspected motor.

Moreover, the analysis of the in-service motor also treats the opportunity of replacing the motor with a properly sized one, whenever the machine is underloaded or another high-efficiency model is available. Having a low level of intrusiveness and offering on-site energy efficiency reports, the method can be an alternative procedure for large motor field testing required by any electric energy or audit study. However, the method also has few limitations. Firstly, it only addresses a certain motor power class; otherwise, the accuracy of the results is significantly affected. Another limitation is determined by an important degree of uncertainty in the case of old or rewound motors because of their modified circuit parameters values. Finally the proposed procedure is designed for motors operating under steady load conditions (a certain duty cycle, *e.g.* S1). If the load varies, a separated investigation for each service is to be performed.

The suggested method could be further improved in terms of its applicability. So, the measured power quality parameters, such voltage and current total harmonic distortion along with their unbalance level, should be better considered. That could be achieved by developing a genuine routine for a precise derating factor determination of the motor operating efficiency parameters. Additionally, the motor replacement study should be also improved by further analyses, such inrush current examination and economic indicators evaluation. The inrush current predetermination would be a useful tool in replacing the actual motor with a high-efficiency model. These rather new motors are known for their considerable higher inrush current amplitude and duration that could affect the motor protection devices or even determine their nuisance tripping. The economic indicators such annual energy savings (AES), cost of corrective action (CCR) or return on investment value (ROI) are also to be considered, being essential criteria in terms of machine replacement decision.

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APPENDIX 1

The list of inspected induction motors and their main parameters are presented in Table 2.

Table 2

List of tested induction machine and their rated parameters

Motor	(a)	(b)	(c)	(d)	(e)
Rated power: P_n [kW]	90	110	132	160	200
Pole pair number: p	2	2	2	2	2
Rated frequency: f_n [Hz]	50	50	50	50	50
Rated voltage: U_n [V]	400	400	400	400	400
Rated speed: n_n [r.p.m.]	2955	2965	2955	2965	2955
Rated efficiency: η_n	0.86	0.88	0.89	0.93	0.94
Rated power factor PF_n ($\cos\varphi_n$)	0.75	0.80	0.85	0.90	0.95

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